Hypothesis about semiweak interaction and experiments with solar neutrinos

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A new concept of solution to the solar neutrino problem, which is based on a hypothesis about the existence of semiweak interaction of electron neutrinos with nucleons mediated by exchange of massless pseudoscalar bosons, is proposed. Owing to about 10 collisions of a solar neutrino with nucleons of the Sun, the fluxes of left- and right-handed solar neutrinos at the Earth surface are approximately equal, and their spectrum is changed in comparison with the one at the production moment. The postulated model with one free parameter provides a good agreement between the calculated and experimental characteristics of the processes with solar neutrinos: $^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar}$, $^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge}$, $\nu_e e^- \to \nu_e e^-$, and $\nu_e D \to e^- pp$.

1. Introduction

The present work explains the discrepancy between the predictions of the standard solar model for the rates of a number of processes caused by solar neutrinos and the results of appropriate experiments by introducing semiweak interaction of electron neutrinos with nucleons, the carrier of which is a massless pseudoscalar boson. At each collision with a nucleon of the Sun due to this interaction, the neutrino changes its handedness and energy. The final mathematically simple procedure for calculating the changes in the solar neutrino spectrum, with making use of only one free parameter and basing entirely on the values of solar neutrino fluxes given by the version BP04 of the standard solar model [1], leads to a remarkable agreement between the theoretical and observed characteristics of experiments of four essentially different types. The probability that this agreement reflects not the true nature of things related to neutrinos, but a game of chance seems to be very low.

Since the work by Gribov and Pontecorvo [2] and till now, the hypothesis of neutrino oscillations held a monopoly position in interpreting the results of experiments with solar neutrinos. It would be highly desirable to compare the results of the present work for the rates of processes, studied in experiments, with the overall results that would be calculated on the basis of formulas of the neutrino oscillation model under some, recognized optimum, values of its parameters. Unfortunately, judging by the extensive review [3], it is difficult, if at all possible, to find in the literature such results connected with oscillations of solar neutrinos.

The situation with those neutrino experiments, in which a manifestation of semiweak interaction caused by a massless pseudoscalar boson is practically impossible, while, as it is believed, a manifestation of neutrino oscillations is possible, is briefly commented in section 12.

2. Hypotesis about the existence of a massless pseudoscalar boson and its interaction

We believe, that the solution to the solar neutrino problem is being provided by logically clear methods of the classical field theory combinated with an additional hypothesis about the existence of semiweak interaction of electron neutrinos with nucleons (u- and d-quarks) mediated by exchange of massless pseudoscalar bosons.

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At that we consider that the neutrino of each sort is described, similarly to the electron, by a bispinor representation of the proper Lorentz group, and its field obeys the Dirac equation. We note that all solutions with positive energy of the massless free Dirac equation, of which two (left-handed and right-handed) can be taken for basic ones, describe various states of the same neutrino. If there is external scalar or pseudoscalar field interacting with the neutrino, then the left and right spinors of neutrino wave vector will both have nonzero values.

The different kinds of hypothetical interactions involving neutrino were considered repeatedly. One of them, proposed by us [4]–[6], was connected with a hypothetical massless axial photon. Now we can assert with sufficient confidence, not going into detail, that it is impossible to solve the solar neutrino problem by means of the axial photon as an interaction carrier. In parallel to this, an assumption about interaction of a hypothetical massless scalar with Majorana neutrino was expressed [7]–[10]. Because the potentional energy $V(r)$ of the standard long-range forces has the behaviour $\sim r^{-1}$ for large enough distance r, only exceedingly faint interaction of such a scalar with others fermions was admitted, practically neither influencing the results of Eotvos type experiments nor the value of the electron magnetic moment and, thereby, the solar neutrino spectrum.

So, we suppose, that there exists a massless pseudoscalar isoscalar boson φ_{ps}, whose interaction with an electron neutrino, a proton and a neutron is described by the following Lagrangian

$$\mathcal{L} = g_{\nu_e ps}\bar{\nu}_e\gamma^5\nu_e\varphi_{ps} + g_{Nps}\bar{p}\gamma^5 p\varphi_{ps} - g_{Nps}\bar{n}\gamma^5 n\varphi_{ps} \tag{1}$$

possessing the invariance under transformations of the orthochronous Lorentz group and under transformations of the isospin group $SU(2)$, or by a similar Lagrangian with u- and d-quarks instead of proton p and neutron n.

We intend neither to maintain, nor to deny the possibility to identify the boson φ_{ps} with the Peccei–Quinn axion, but we take into account the unsuccessfulness of experimental search for the axion and therefore postulate, for the sake of simplicity, the masslessness of the introduced boson, not excluding small enough values of its mass. The pseudo-scalar boson φ_{ps} is considered not interacting with the electron at tree level because it is impossible to fulfil simultaneously the three conditions: the values of coupling constants of this boson with the electron neutrino and the electron should be of the same order; the neutrino produced in the center of the Sun with the energy of the order 1 Mev should undergo at least one collision with some electron of the Sun; the contribution of such a boson to the value of the electron magnetic moment should not exceed the uncertainty limits admissible by the standard theory and experiments [11]. We do not exclude that the interaction of boson φ_{ps} with neutrinos of different sorts (ν_e, ν_μ, and ν_τ) is nonuniversal, i.e., characterized by different coupling constants.

Note that the massless axial field cannot manifest itself in Eotvos type experiments, as the interaction of two nucleons mediated by it is similar to the magnetic interaction of spins, namely [12]: $V(r) \sim r^{-3}[\boldsymbol{\sigma}_1\boldsymbol{\sigma}_2 - 3(\boldsymbol{\sigma}_1\mathbf{n})(\boldsymbol{\sigma}_2\mathbf{n})]$, where $\boldsymbol{\sigma}_i$ are the fermion spin matrices. Here is another simple reason in this respect. For the standard long-range forces, the differential cross section of the elastic scattering of two charged particles described by the Rutherford formula has a pole at zero of the square of the momentum transfer, and the total cross section of such a scattering is infinite. In contrast to this, the differential cross section of the elastic scattering of two fermions caused by a massless axial boson exchange has no pole, and total cross section of such a scattering is finite (see formulas (2) and (4)).

3. Cross-sections and kinematics of the elastic neutrino-nucleon scattering

The differential cross-section of the elastic scattering of the left- or right-handed electron neutrino with initial energy ω_1 on a rest nucleon with mass M, obtained on the basis of

Lagrangian (1), is given by expression

$$d\sigma = \frac{(g_{\nu_e ps} g_{Nps})^2}{32\pi M \omega_1^2} d\omega_2, \tag{2}$$

where ω_2 is the scattered neutrino energy, which, as it results from the energy-momentum conservation law and from the formula (2), can take evenly distributed values in interval

$$\frac{\omega_1}{1 + 2\omega_1/M} \leq \omega_2 \leq \omega_1. \tag{3}$$

The total cross-section of the elastic $\nu_e N$-scattering found from relations (2) and (3) is

$$\sigma = \frac{(g_{\nu_e ps} g_{Nps})^2}{16\pi M^2} \cdot \frac{1}{(1 + 2\omega_1/M)} \tag{4}$$

and, consequently, the mean free path of the solar neutrino before its collision with any nucleon practically does not depend on the energy ω_1 because its maximal value is about 16 MeV [13].

The first consequence of the interaction (1) is that at each collision with a nucleon caused by an exchange of axial boson, the neutrino changes its handedness from left to right and vice versa. We take into account that solar neutrinos are produced in different areas distanced from each other by 0.1 up to 0.3 solar radius on the average (this and other information about solar neutrinos is taken from the review [13]), and that, anyhow, they undergo different number of collisions with nucleons before escaping from the Sun. Then it seems reasonable to consider that, at an average number of collisions of the order of 10, the fluxes of left- and right-handed solar neutrinos at the Earth surface are approximately equal. The contributions from right-handed neutrinos to the charged current processes at low energies are extremely small. For example, the analysis of the nucleosynthesis in the early Universe gives the following estimate [14]: $M_{W_R} > 3.3$ TeV, if $g_R = g_L$. The latter condition is automatically fulfilled in the initially P-invariant model of the electroweak interactions [15]. Therefore, the flux of the effective (left-handed) neutrino arriving at the Earth is approximately twice less than that expected in the absence of any interaction acts after their production in the Sun.

The second consequence of the interaction of the solar neutrino with a nucleon resulting from relations (2) and (3) is the neutrino energy decrease, on the average, by the value of

$$\Delta\omega_1 = \frac{\omega_1^2}{M} \cdot \frac{1}{1 + 2\omega_1/M} \tag{5}$$

in comparison with the initial energy. The formula (5) shows that the relative single-shot change in the energy $\Delta\omega_1/\omega_1$ for solar neutrinos from decays of ^{8}B (their average energy equals 6.7 MeV) playing the dominant role in transitions $^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar}$ is by one order higher than that for p-p-neutrinos (their maximal energy equals 0.423 MeV) giving the most essential contribution to transitions $^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge}$. This conclusion together with the first consequence gives clear qualitative understanding of the features of experimental results with chlorine and gallium.

When calculating the rates of a number of processes caused by solar neutrinos, we adhere to the most simple scenario. The only free parameter of the considered model is the effective number n_0 of collisions of a neutrino with nucleons, which occur from the production to the exit of this neutrino from the Sun, with n_0 being independent from the neutrino initial energy. We suppose that this number affects the solar neutrino spectrum keeping intact the proportion between the different handedness states at the exit from the Sun. Regarding the methods acceptable for calculations (say, in FORTRAN, as we did it), we have considered two variants to describe the energy distribution of neutrinos, having fixed initial energy ω_i, after n_0 collisions with nucleons. In the first variant, the energy attributed to a neutrino after each collision is

equal to the mean value of the kinematic interval (3), so that we have sequentially for zero, one, ..., n_0 collisions

$$\omega_{0,i} = \omega_i, \quad \omega_{1,i} = \omega_{0,i}\frac{1+\omega_{0,i}/M}{1+2\omega_{0,i}/M}, \quad \ldots, \quad \omega_{n_0,i} = \omega_{n_0-1,i}\frac{1+\omega_{n_0-1,i}/M}{1+2\omega_{n_0-1,i}/M}. \tag{6}$$

In the second variant, it is assumed that, as a result of each collision with a nucleon, the neutrino energy takes one of the two limiting values of the interval (3) with equal probability and, by that, after n_0 collisions the initial level of energy ω_i turns into a set of n_0+1 binomially distributed values which elements are listed below:

$$E_{1,i} = \omega_i, \quad E_{2,i} = \frac{E_{1,i}}{1+2E_{1,i}/M}, \quad \ldots, \quad E_{n_0+1,i} = \frac{E_{n_0,i}}{1+2E_{n_0,i}/M}. \tag{7}$$

Both variants yield close results. As the second variant is more comprehensible in its logical plan than the first, we use it everywhere, except for calculating the rate of the deuteron disintegration process $\nu_e D \to e^- pp$ where there is a problem of overflow of the fortran program stack.

Let us turn now to specific experiments on registration of solar neutrinos.

4. The process $\nu_e + {}^{37}\mathrm{Cl} \to e^- + {}^{37}\mathrm{Ar}$

The first experiment of this type [16] has consisted in studying the process $\nu_e + {}^{37}\mathrm{Cl} \to e^- + {}^{37}\mathrm{Ar}$, having the threshold energy 0.814 MeV. Now the experimental rate of such transitions is considered equal to $2.56 \pm 0.16 \pm 0.16$ SNU (1 SNU is 10^{-36} captures per target atom per second) [17]. At the same time, theoretical calculations based on the standard solar model (SSM) give though different, but significantly greater values, for example: 7.9 ± 2.6 SNU [13] and 8.5 ± 1.8 SNU [1].

We take from Refs. [13], [18], and [19] the tabulated values of a number of quantities which are necessary to us for calculating the rates of transitions ${}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar}$ and ${}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge}$ induced by solar neutrinos.

We use the dependence of the cross-section of the process of neutrino absorption by chlorine on the neutrino energy E, presented in the table IX and partly in the table VII of Ref. [13], and we assign for this cross-section a linear interpolation in each energy interval. We note the strong enough dependence of the mentioned cross-section on energy E (expressed below in MeV) [20]: $\sigma^{\mathrm{Cl}}(E) \sim E^{2.85}$, if $E \in [1, 5]$, and $\sigma^{\mathrm{Cl}}(E) \sim E^{3.7}$, if $E \in [8, 15]$. Therefore it is necessary to expect, that the decrease in energy of solar neutrinos as a result of their collisions with nucleons will affect the rate of ${}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar}$ transitions stronger than the rate of elastic neutrino-electron scattering.

The energy values of the neutrino from ${}^8\mathrm{B}$, spreading from 0 to about 16 MeV, are given in the table of Ref. [18] in the form of set $\omega_i^B = i\Delta^B$, where $i = 1, \ldots, 160$, $\Delta^B = 0.1$ MeV, and their distribution is expressed through probability $p(\omega_i^B)$ of that neutrinos possess energy in an interval $(\omega_i^B - \Delta^B/2,\ \omega_i^B + \Delta^B/2)$. Each of the energy distributions in the interval [0, 1.73] MeV for neutrinos from ${}^{15}\mathrm{O}$ and in the interval [0, 1.20] MeV for neutrinos from ${}^{13}\mathrm{N}$ is presented in tables of Ref. [19] for 84 points, and the distribution for neutrinos from *hep* is given in the table of Ref. [13] for 42 values of energy in the interval [0, 18.8] MeV. The energy spectrum of neutrinos from ${}^7\mathrm{Be}$ has two lines $\omega_1^{Be} = 0.862$ MeV (89.7%) and $\omega_2^{Be} = 0.384$ MeV (10.3%), and from *pep* has one line $\omega_1^{pep} = 1.442$ MeV. For solar neutrino fluxes at the Earth surface, the values (in units of $\mathrm{cm}^{-2}\mathrm{s}^{-1}$) presented in Ref. [1] are taken: $\Phi({}^8\mathrm{B}) = 5.79 \times 10^6(1 \pm 0.23)$, $\Phi({}^7\mathrm{Be}) = 4.86 \times 10^9(1 \pm 0.12)$, $\Phi({}^{15}\mathrm{O}) = 5.03 \times 10^8(1^{+0.43}_{-0.39})$, $\Phi(pep) = 1.40 \times 10^8(1 \pm 0.05)$, $\Phi({}^{13}\mathrm{N}) = 5.71 \times 10^8(1^{+0.37}_{-0.35})$, $\Phi(hep) = 7.88 \times 10^3(1 \pm 0.16)$. For all that in the calculations, we use only the average values of the fluxes without involving uncertainty into any estimations or conclusions.

In view of the assumption that the fluxes of the left-handed neutrino at the Earth surface are equal to half of the above-mentioned fluxes, the formulas for calculating the contributions to the rate of transitions $^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar}$ caused by neutrinos from ^{8}B and ^{7}Be can correspondingly be presented in the form

$$V(^{37}\mathrm{Cl} \mid \mathrm{B}) = 0.5\Phi(^{8}\mathrm{B}) \sum_{i=1}^{160} \Delta^{B} p(\omega_i^{B}) \sum_{n=1}^{n_0+1} \frac{n_0!}{2^{n_0}(n-1)!(n_0+1-n)!} \sigma^{\mathrm{Cl}}(E_{n,i}^{B}), \tag{8}$$

$$V(^{37}\mathrm{Cl} \mid \mathrm{Be}) = 0.5 \times 0.897\Phi(^{7}\mathrm{Be}) \sum_{n=1}^{n_0+1} \frac{n_0!}{2^{n_0}(n-1)!(n_0+1-n)!} \sigma^{\mathrm{Cl}}(E_{n,1}^{Be}), \tag{9}$$

where energy values $E_{n,i}^{B}$ and $E_{n,1}^{Be}$ are given by the formula (7), in which the quantity ω_i needs to be set equal to ω_i^{B} and ω_1^{Be} accordingly. The contributions from neutrinos from ^{15}O, ^{13}N, and *hep* are calculated by a formula similar to (8), and the contribution from *pep* does by a formula similar to (9).

Before we proceed to calculations using formulas of the type (8) and (9) with nonzero value of the number of neutrino-nucleon collisions n_0, we check how much are the results, obtained with using the tabulated and interpolated values for the cross-section $\sigma^{\mathrm{Cl}}(E)$ under the condition of free motion of neutrinos in the Sun, close to what are obtained in Ref. [13] on the basis of more precise calculations, though at slightly fifferent spectra and flux values. This comparison is reflected in table 1.

We find that the rate of transitions $^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar}$ calculated within the framework of interaction (1) agrees with the experimentally measured one if the number of neutrino-nucleon collisions n_0 is 13 ± 3, when the rate of transitions equals to $2.55^{+0.27}_{-0.24}$ SNU. The calculations concerning all of the discussed below processes give in their integrity the best agreement with experimental results if $n_0 = 10$, and, therefore, this number is present in table 1 and in the rest of the paper.

Table 1. The rate of transitions $^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar}$ in SNU.

	^{8}B	^{7}Be	^{15}O	*pep*	^{13}N	*hep*	Total
SSM [13]	6.1	1.1	0.3	0.2	0.1	0.03	7.9
Interpolations, no interactions	6.21	1.05	0.35	0.22	0.09	0.02	7.94
Interaction (1), $n_0 = 10$	2.05	0.44	0.17	0.11	0.04	0.01	2.82

5. The process $\nu_e + {}^{71}\mathrm{Ga} \to e^- + {}^{71}\mathrm{Ge}$

Let us turn now to the process $\nu_e + {}^{71}\mathrm{Ga} \to e^- + {}^{71}\mathrm{Ge}$ having the threshold energy 0.233 MeV. The latest experiments have given the following values for the rate of this process: $65.4^{+3.1+2.6}_{-3.0-2.8}$ SNU [21] and $62.9^{+6.0}_{-5.9}$ SNU [22]. From the theoretical results, which are worthy mentioning, we note two: 132^{+20}_{-17} SNU [13] and 131^{+12}_{-10} SNU [1].

We use the neutrino energy dependence of the cross-section of the process with gallium $\sigma^{\mathrm{Ga}}(E)$ presented in the table II of Ref. [19], and interpolate it inside the each interval by a linear function. In addition to the information written above on the neutrino fluxes, some data about neutrinos from *p-p* is still required. The tabulated energy spectrum of such neutrinos, available in Ref. [13], spreads from 0 to 0.423 MeV and is given by a set of 84 points. The flux of solar neutrinos from *p-p* at the Earth surface is taken equal to $\Phi(pp) = 5.94 \times 10^{10}(1 \pm 0.01)$ cm^{-2}s^{-1} [1].

We calculate the contributions to the rate of transitions $^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge}$ brought by solar neutrinos from *p-p*, ^{8}B, ^{15}O, ^{13}N, and *hep*, with the formula similar to (8), and the contributions brought by two lines of ^{7}Be and by one line of *pep*, with the formula similar to (9). The results of calculations are presented in table 2.

Table 2. The rate of transitions $^{71}\text{Ga} \to {}^{71}\text{Ge}$ in SNU.

	p-p	^{7}Be	^{8}B	^{15}O	^{13}N	*pep*	*hep*	Total
SSM [13]	70.8	34.3	14.0	6.1	3.8	3.0	0.06	132
Interpolations, no interactions	69.8	34.9	14.0	5.7	3.4	2.9	0.05	130.7
Interaction (1), $n_0 = 10$	34.7	17.2	5.0	2.8	1.7	1.4	0.02	62.8

The fact that the theoretical value of the rate of transitions $^{71}\text{Ga} \to {}^{71}\text{Ge}$ at $n_0 = 10$ agrees with the above-mentioned experimental values is an important evidence, firstly, in favour of our assumption about the approximate equality of the fluxes of the left- and right-handed solar neutrinos at the Earth surface and, secondly, in favour of the consequence (5), resulting from Lagrangian (1), about decreasing the relative neutrino energy change at a single-shot collision with decreasing energy.

6. The process $\nu_e + e^- \to \nu_e + e^-$

Let us turn to consideration of the process of elastic scattering of solar neutrinos on electrons $\nu_e e^- \to \nu_e e^-$, taking into account the conditions and the results of experiments at Super-Kamiokande [23]–[25] and at the Sudbury Neutrino Observatory (SNO) [26]–[29].

The differential cross-section of elastic scattering of the left-handed neutrino with initial energy ω on a rest electron with mass m is given by the formula (see, for example, Ref. [30], [31])

$$\frac{d\sigma_{\nu e}}{dE} = \frac{2G_F^2 m}{\pi}\left[g_L^2 + g_R^2\left(1 - \frac{E-m}{\omega}\right)^2 - g_L g_R \frac{m(E-m)}{\omega^2}\right] \equiv f_{\nu e}(\omega, E), \tag{10}$$

where E is the energy of the recoil electron. For the scattering of the electron neutrino, we have in the Weinberg–Salam model of electroweak interations

$$g_L = \frac{1}{2} + \sin^2\theta_W, \quad g_R = \sin^2\theta_W, \tag{11}$$

where it is necessary to set $\sin^2\theta_W = 0.231$.

On the basis of the energy-momentum conservation law, we obtain that the recoil electron can get the energy E if the energy ω of the incident neutrino satisfies the condition

$$\omega \geq \frac{E - m + \sqrt{E^2 - m^2}}{2} \equiv h_{\nu e}(E). \tag{12}$$

At setting up an experiment on the elastic neutrino-electron scattering, it is considered that a distinction between the true energy E of the recoil electron and its reconstructed (effective) energy E_{eff} is given by the Gaussian probability density

$$P(E_{\text{eff}}, E) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(E_{\text{eff}} - E)^2}{2\sigma^2}\right], \tag{13}$$

where the parameter σ, being a function of the energy E, depends on the features of an experimental set-up.

Since in all of the discussed experiments the lower limit E_c for the reconstructed energy E_{eff} is introduced, and it is not less than 3 MeV, then the observable events are practically completely generated by the solar neutrinos from ^{8}B, while the contribution from neutrinos from *hep* is very small. The contribution to the rate of the scattering of neutrinos from ^{8}B

on electrons, when the reconstructed energy $E_{\rm eff}$ belongs to the interval from E_k up to E_{k+1} ($E_k \geq E_c$), is calculated according to the formula

$$V(\nu e \mid {\rm B} \mid\mid [E_k, E_{k+1}]) = 0.5\Phi(^8{\rm B}) \int_{E_k}^{E_{k+1}} dE_{\rm eff} \int_{1 \text{ Mev}}^{16 \text{ Mev}} dE[P(E_{\rm eff}, E)$$

$$\times \sum_{i=1}^{160} \Delta^B p(\omega_i^B) \sum_{n=1}^{n_0+1} \frac{n_0!}{2^{n_0}(n-1)!(n_0+1-n)!} f_{\nu e}(E_{n,i}^B, E)\theta(E_{n,i}^B - h_{\nu e}(E))], \tag{14}$$

where $\theta(x)$ is the Heaviside step function. The contribution from neutrinos from *hep* is found by the similar formula. The result of this or that experiment and, also, the theoretical calculation on the basis of the formula (14) are expressed through the effective (either observable, or equivalent) flux of neutrinos from ^{8}B, $\Phi_{eff}(^8{\rm B})$, which do not undergo any changes between the production place in the Sun and the experimental apparatus on the Earth. Connection between such a result or calculation and the effective flux is given by the following relation

$$V(\nu e \mid {\rm B} + hep \mid\mid [E_c, 20 \text{ MeV}]) = \Phi_{eff}^{\nu e}(^8{\rm B}) \int_{E_c}^{20\text{MeV}} dE_{\rm eff} \int_{1 \text{ Mev}}^{16 \text{ Mev}} dE[P(E_{\rm eff}, E)$$

$$\times \sum_{i=1}^{160} \Delta^B p(\omega_i^B) f_{\nu e}(\omega_i^B, E)\theta(\omega_i^B - h_{\nu e}(E))]. \tag{15}$$

Let us notice here, that the Gaussian distribution (13) has essential influence on the bin $[E_k, E_k + 0.5 \text{ MeV}]$ distribution (14) of the rate of νe-scattering events and has only small influence on the value of the effective neutrino flux found from equality (15).

Some details of the experiments and of our calculations concerning the elastic scattering of solar neutrinos on rest electrons are presented in table 3, where $T = E - m$.

Table 3. Effective fluxes of neutrinos found from the process $\nu_e e^- \to \nu_e e^-$ (E_c, E, and T are given in MeV, and the fluxes are in units of 10^6 cm^{-2}s^{-1}).

References	E_c	σ	Experimental $\Phi_{eff}^{\nu e}(^8{\rm B})$	Eq. (1), $n_0 = 10$: $\Phi_{eff}^{\nu e}(^8{\rm B})$
SK III [25]	5.0	$-0.123 + 0.376\sqrt{E} + 0.0349E$	$2.32 \pm 0.04 \pm 0.05$	2.32
SK II [24]	7.0	$0.0536 + 0.520\sqrt{E} + 0.0458E$	$2.38 \pm 0.05^{+0.16}_{-0.15}$	2.07
SK I [23]	5.0	$0.2468 + 0.1492\sqrt{E} + 0.0690E$	$2.35 \pm 0.02 \pm 0.08$	2.32
SNO III [29]	6.5	$-0.2955 + 0.5031\sqrt{T} + 0.0228T$	$1.77^{+0.24+0.09}_{-0.21-0.10}$	2.08
SNO IIB [28]	6.0	$-0.131 + 0.383\sqrt{T} + 0.0373T$	$2.35 \pm 0.22 \pm 0.15$	2.17
SNO IIA [27]	6.0	$-0.145 + 0.392\sqrt{T} + 0.0353T$	$2.21^{+0.31}_{-0.26} \pm 0.10$	2.17
SNO I [26]	5.5	$-0.0684 + 0.331\sqrt{T} + 0.0425T$	$2.39^{+0.24+0.12}_{-0.23-0.12}$	2.24

7. The process $\nu_e + D \to e^- + p + p$

Let us dwell now on the process of deuteron desintegration by solar netrinos caused by the weak charged current interactions, $\nu_e D \to e^- pp$. The needed differential cross-section of this process, $d\sigma_{cc}/dE \equiv f_{cc}(\omega, E)$, as a function of energy ω of the incident left-handed electron neutrino and the energy E of the produced electron is found in the tabulated form on a Website [32], which has resulted from the field-theoretical analysis of the νD-reaction presented in Ref. [33]. In the tables of Ref. [32], the intervals in ω are of 0.2 MeV, and the intervals in E are varied in length. First, we extrapolate the results of the tables into intervals in E equal to 0.2 MeV, and then, in the fortran program, we assign a linear extrapolation of the cross-section in each interval in ω.

The kinematic condition for the neutrino energy needed for the deuteron desintegration has the form (see, for example, Ref. [34])

$$\omega \geq E + E_D + \delta \equiv h_{cc}(E), \tag{16}$$

where $E_D = 2.2246$ MeV is the binding energy of the deuteron, and $\delta = M_p - M_n = -1.2933$ MeV is the mass difference between the proton and the neutron.

We neglect the contribution to the deuteron desintegration from neutrinos from *hep* and carry out the calculations of the rate of the process $\nu_e D \to e^- pp$ by the formula similar to (14):

$$V(cc \mid \mathrm{B} \mid\mid [E_k, E_{k+1}]) = 0.5\Phi(^8\mathrm{B}) \int_{E_k}^{E_{k+1}} dE_{\mathrm{eff}} \int_{1 \text{ Mev}}^{16 \text{ Mev}} dE[P(E_{\mathrm{eff}}, E)$$

$$\times \sum_{i=1}^{160} \Delta^B p(\omega_i^B) f_{cc}(\omega_{n_0,i}^B, E)\theta(\omega_{n_0,i}^B - h_{cc}(E))], \tag{17}$$

where the energy value $\omega_{n_0,i}^B$ is given by the formula (6), in which the quantity ω_i has to be taken equal to ω_i^B. The appropriate effective neutrino flux $\Phi_{eff}^{cc}(^8\mathrm{B})$ is found from the relation similar to (15).

The results of the SNO collaboration experiments and of our calculations are presented in table 4.

Table 4. Effective fluxes of neutrinos found from the process $\nu_e D \to e^- pp$ (E_c is given in MeV, and the fluxes are in units of 10^6 cm^{-2}s^{-1}).

References	E_c	Experimental $\Phi_{eff}^{cc}(^8\mathrm{B})$	Eq. (1), $n_0 = 10$: $\Phi_{eff}^{cc}(^8\mathrm{B})$
SNO III [29]	6.5	$1.67^{+0.05+0.07}_{-0.04-0.08}$	1.63
SNO IIB [28]	6.0	$1.68^{+0.06+0.08}_{-0.06-0.09}$	1.75
SNO IIA [27]	6.0	$1.59^{+0.08+0.06}_{-0.07-0.08}$	1.75
SNO I [26]	5.5	$1.76^{+0.06+0.09}_{-0.05-0.09}$	1.85

Noting good enough agreement between the results of our calculations and the results of experiments concerning the effective neutrino fluxes which correspond to the events of elastic νe-scattering and the reaction $\nu_e D \to e^- pp$, we draw attention to the fact that the difference between theoretical values of the effective fluxes describing the two processes is due to the change in the shape of the solar neutrino spectrum because of their collisions with the nucleons of the Sun.

8. Unsolved theoretical problem

We have still left without detailed consideration the deuteron desintagration $\nu D \to \nu np$ caused by neutral currents of solar neutrinos, which is investigated in SNO experiments. In view of our hypothesis about the existence of the interaction described by Lagrangian (1), disintegration of the deuteron into a neutron and a proton is described by two non-interfering processes, which differ in neutrino handedness either in the initial or in the final state. The first process which is practically completely due to left-handed neutrinos is standard, i.e. it is due to the exchange of the Z-boson. The calculation of its characteristics is described, for example, in the work [33] where the tabulated values of its total cross section depending on the energy of the incident neutrinos are also presented. The second process involving both left- and right-handed neutrinos is due to the exchange of the massless pseudoscalar boson. As the interaction

constants of the pseudoscalar boson with the proton and the neutron in Lagrangian (1) have opposite values, the amplitude of the second process in the one-nucleon impulse approximation implying equal p and n masses of a neutron and a proton is zero. The problem of accurate calculations of the cross section of the second process with the mass difference between the neutron and the proton taken into account is enough difficult and complicated, so that we have not attempted solving it. Note however the reasonableness of estimating the total deuteron disintegration cross section due to the interaction (1) as, by its order of magnitude, the total elastic neutrino scattering on a nucleon times $[(M_n - M_p)/M]^2$, that with the constants (18) makes $\sim 1.7 \cdot 10^{-42}$ cm^2. At the same time, the total cross section of the standard deuteron disintegration process at the neutrino energy $8 \div 12$ MeV is equal to $(0.56 \div 1.9) \cdot 10^{-42}$ cm^2 (see table 1 in the work [33]).

9. Unfulfilled experimental tasks

It is possible in principle to provide an answer to the question of the change of the spectrum shape of solar neutrinos from ^{8}B by an experimental measurement of the event rate distribution for the process $\nu_e e \to \nu_e e$ or $\nu_e D \to e^- pp$ in the energy of the scattered or produced electrons. In the works by Super-Kamiokande and SNO collaborations, this question, however, was not put in an evident view and by that had no experimental solution. In the paper [23] containing the most detailed description of the data processing, the solar neutrino flux is extracted from the likelihood function, and the authors say about one of the quantities Y_i entering into this function: "Y_i represent the expected fraction of signal evens in the ith energy bin". Thus, in the processing of the experimental results on νe-scattering, the shape of the event rate distribution in the recoil electron energy expected in the standard solar model is laid from the beginning. We find another evidence for this in Ref. [35], containing a correction of two mistakes made in Ref. [25]. One of them concerns "uncertainties... based on the Monte Carlo simulation ^{8}B solar neutrino events", and the matter of the other is: "The energy dependence of the differential interaction cross-section between neutrinos and electrons was accidentally eliminated". The correction of the mentioned mistakes should not have influenced in any way the event rate distribution in the energy of the recoil electrons if it had the purely experimental origin. But by comparing table A.1 from Ref. [35] with table VI from Ref. [25], we detect that, along with the decrease in the "expected rate" in every energy bin, there is also a simultaneous decrease in the "observable rate". So, the distributions in the energy bins of the "observable rate" of νe-events at all positions of the Sun as presented in the tables of Refs. [23]–[25] have no value for theoretical conclusions as they reflect only what was initially laid in them and passed through fitting the likelihood function.

Let us note in addition that the final electron energy distributions for the νD- and νe-processes presented in the table XXII of Ref. [36] show, over vivid irregularities, almost full identity in their shapes for the phase I and phase II of the SNO experiment. An opinion is free or involuntarily formed, that this identity has no purely experimental origin and comes from using in both phases the same programs for distributing the full number of events among the energy bins.

10. Coupling constants

Let us find the value of the constant $g_{ps\nu_e} g_{psN}$ starting from the point that the electron neutrinos during their movement in the Sun undergo a small number (of order of 10) of collisions with nucleons. Using the density values of the Sun matter varying with the distance from the Sun center as tabulated in Ref. [13], we find that a tube of 1 cm^2 cross-section spearing spreading from the center to the periphery of the Sun contains 1.5×10^{12} grams of matter and, consequently, 8.9×10^{35} nucleons. From here, and on the basis of relation (4) and the

assumption that a neutrino passes in the Sun through 0.7 to 0.9 of the amount of matter in the mentioned tube before colliding with a nucleon, we obtain

$$\frac{g_{\nu_e ps} g_{Nps}}{4\pi} = (3.2 \pm 0.2) \times 10^{-5}. \tag{18}$$

Thus, the product of constants of the postulated interaction of a massless pseudoscalar boson with electron neutrinos and nucleons is by several orders of magnitude smaller than the constants of electromagnetic and weak interactions, respectively α and $g^2/4\pi$. Therefore, the postulated interaction could be named superweak. However, by virtue of that the total cross-section of such a neutrino-nucleon interaction at a low energy, as it is the case for solar neutrinos, is much larger than that of the standard weak interaction via Z-boson exchange, we prefer to call the postulated interaction semiweak.

11. A few remarks

At ten collisions of a solar neutrino with nucleons, the neutrino energy output from the Sun decreases approximately by 0.3% in comparison with the value expected in SSM, what is less than the theoretical uncertainty of the neutrino flux value, 1%. This gives us the firm basis to think, that the postulated interaction of stellar neutrinos with nucleons has very little effect on the evolution of this or that star.

The answer to the question about the presence or absence of the interaction of a massless pseudoscalar boson with a muon neutrino should be sought in experiments with accelerator neutrinos.

12. Beyond the framework of the semiweak interaction

Over the years, many neutrino experiments have been set to establish neutrino oscillations. Some results of such experiments can be found in the review papers [3] and [37]. Their essential element is the fact, that in interpreting results of three types of experiments on the basis of the neutrino oscillation model, three various branches of this model are used. Namely, the experiments with solar neutrinos are mainly associated with two-neutrino (2ν) oscillations with parameters θ_{12} and Δm_{21}; experiments with antineutrinos from reactors, the distance to which makes up to several thousand meters, refer to 2ν-oscillation parameters θ_{13} and Δm_{31}; experiments with atmospheric and accelerator neutrinos are mapped onto 2ν and 3ν-oscillations which include the parameters θ_{23} and Δm_{32}. Consequently, an alternative explanation of the results of the solar neutrino experiments has no effect on the admissibility of interpreting the neutrino experiments of other types with the oscillation model and vice versa.

A special place with respect to the solar neutrino experiments is occupied only by experiments in KamLAND, registering antineutrinos from tens of reactors located at hundreds kilometers away from the experimental unit, because the interpretations of those and other experiments based on the oscillation model correlate with each other. A discussion on the nature of the difference between the expected and observed results with KamLAND is given in a separate paper [38].

13. Conclusion

It is surprising and wonderful, that some aspects of the short-term Brownian motion of a electron neutrino in the inhomogeneous but spherically symmetric Sun medium manifesting themselves in a number of experiments, allow so simple and efficient mathematical and physical description on the basis of the hypothesis about the existence of semiweak interactions between electron neutrinos and nucleons.

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